

The Case for Impulse - Analysis of Conventional Structures Subjected to Blast Loads

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Bio: Mr. Barker is Vice President for Extreme Loads and Structural Risk for ABS Consulting. He has a B.S.C.E from University of Arkansas (1983) and 27 years experience in the design and analysis of structures for blast and fragment loading. He has performed hazard analyses for government and commercial clients to quantify risks resulting from accidental explosions. Mr. Barker has extensive experience in the field of explosives safety including Q-D application, equivalent protection analysis, and debris research.

Abstract: Buildings designed for conventional loads (wind, snow, live) often have limited capacity to resist blast loads. Understanding the performance of these conventional structures when subjected to accidental explosions is important for determining protection of personnel and equipment.

A variety of references provide estimates of performance for conventional structures at selected overpressure levels. Unfortunately, peak blast pressure alone is not sufficient to determine performance in most cases. Blast load duration is equally important when considering structural response. Load duration along with peak pressure defines the blast impulse. Peak pressure and impulse are both important and necessary to determine structural response and hazards produced by both structural and non-structural components of a building. Peak pressure level tables are widely used, primarily because much of the available data was developed from nuclear weapons effects testing with very long duration loads. Additionally, overpressure is a parameter that most people have an innate understanding of whereas impulse is a parameter that is initially much harder to relate to damage effects

This paper examines the response of building components to both pressure and impulse, identifies the importance of each parameter, and explores situations in which impulse controls response and debris hazards. It is intended to provide a greater understanding of the importance of impulse for persons who do not have a structural dynamics background.

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Introduction

Overpressure is a commonly understood blast parameter that is readily associated with building damage. Blast capacity is often described in terms of overpressure level without much thought to the duration of the blast load. In reality, duration of the load is extremely important to damage produced by blast loads. Blast overpressure is conceptually easier to understand as people are familiar with the physical meaning of pressure. This focus on overpressure is very much akin to referring to electricity in terms of voltage without consideration of amperage. The time honored adage “volts sting, amps kill” is recognition of the importance of amperage when considering electrical hazards. In the discussion below, an examination of the importance of impulse is provided.

Blast Loads – A Closer Look

Blast loads from high explosives detonations are typically characterized by an instantaneous rise in pressures above ambient pressure (overpressure) to a peak value followed by a rapid decay back to ambient followed by an underpressure (negative pressure). This underpressure is most often much lower in amplitude but longer in duration than the positive phase portion of the load. A typical blast load in the form of a pressure-time history is shown in Figure 1. A blast load of this type is characterized by the peak pressure, load duration and impulse. This latter value is the integral of the pressure-time curve and is shown as a function of time in the figure. A simplified form of the blast load, a linear decay as shown in Figure 2, is often used. In this form, the total impulse of the actual pressure decay is preserved and an equivalent load duration is computed.

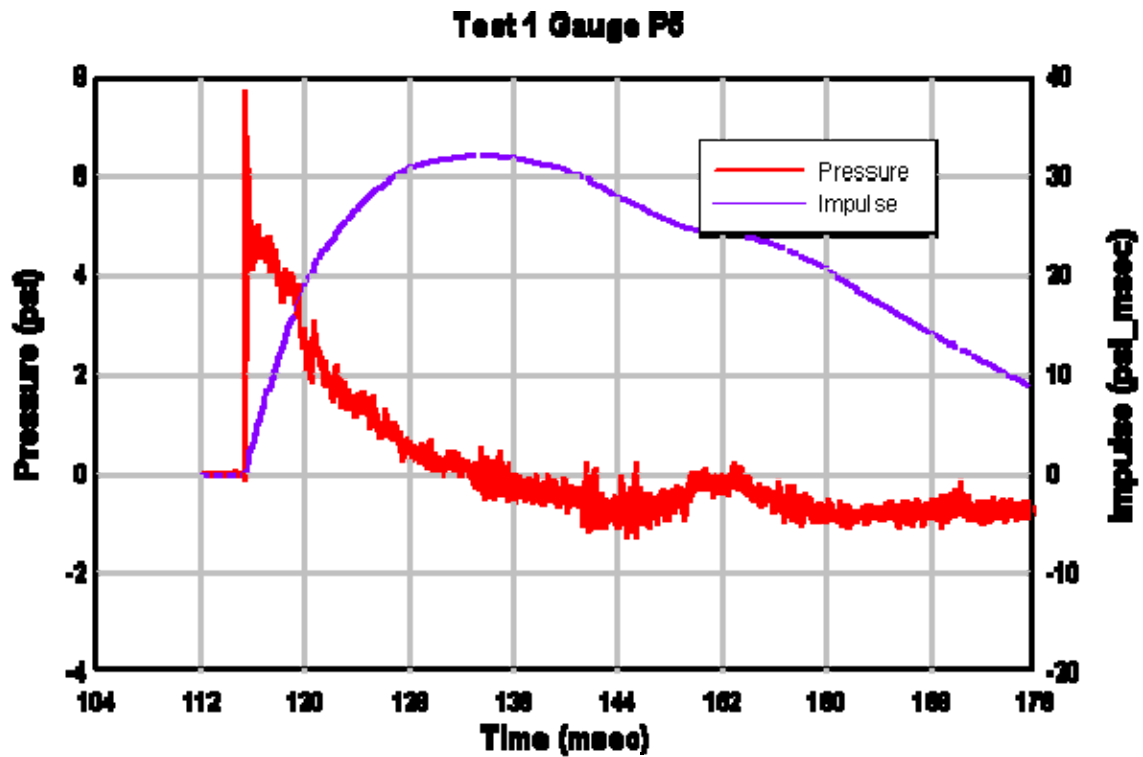


Figure 1 Pressure-Time History for High Explosives Detonation

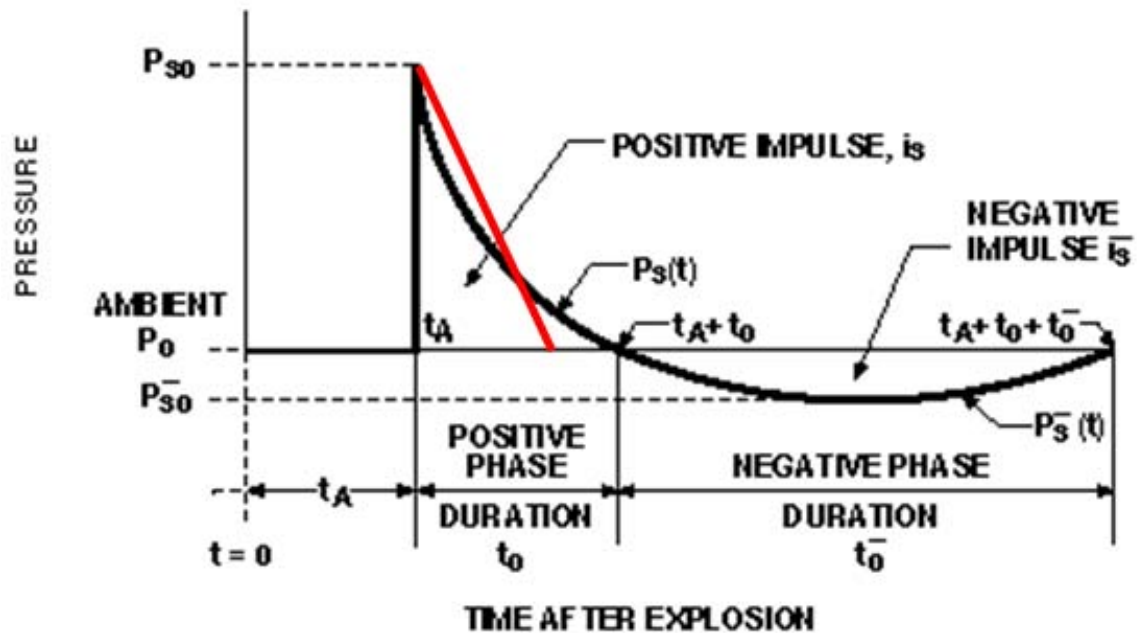


Figure 2 Idealized Pressure-Time History

Impulse then is a measure of the total applied load. It is a key parameter when considering the response of structural and non-structural components to blast loads. In general, response will be dependent on the impulse unless the component is so stiff that it reaches a peak deflection and begins to rebound before the end of the positive

phase of the blast wave. These components are referred to as “pressure sensitive”. Those that respond to the total load phase are said to be “impulse sensitive”. Pressure and impulse sensitivity can be evaluated by comparing the positive load duration (T_d) to the natural period of vibration (T_n) of the component. The period of vibration is a function of the component mass and stiffness.

Pressure vs. Impulse

It is convenient to examine this response phenomenon using single-degree-of-freedom (SDOF) analysis. This technique is a numerical analysis of a simple spring-mass system which represents a structural component as shown in Figure 3. A very useful tool which arises from the SDOF analysis technique is the pressure-impulse (P-I) diagram. A generic P-I diagram is shown in Figure 4. Each curve on the P-I diagram represents a constant value of deflection. Any pressure and impulse pair on a given curve produces the same deflection as all other pressure and impulse pairs on the curve. Any P-I pair which falls above or to the right of a curve produces a higher response (damage) than that represented by the curve.

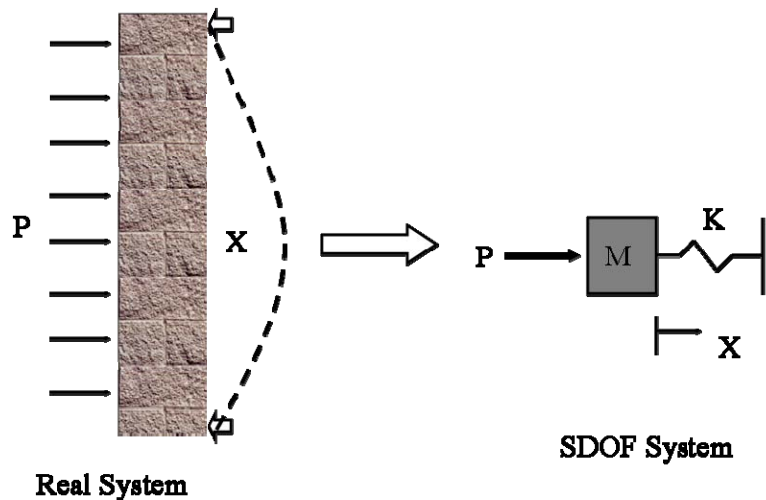


Figure 3 Real and SDOF System Representation

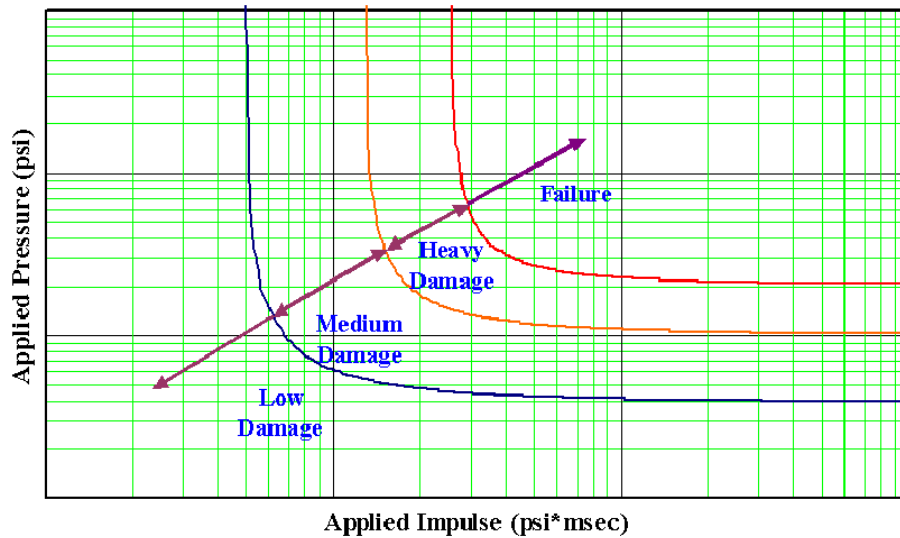


Figure 4 Pressure-Impulse Diagram

The curves are asymptotic on both the pressure and impulse axes. The pressure asymptote defines a response level at that pressure regardless of the load duration. Even if the impulse is infinitely large, the response will not increase. This pressure asymptote is determined by equating the strain energy capacity of the component to work done by the blast load. This work done is force times distance or blast pressure times peak deflection.

The impulse asymptote is slightly more complicated and is determined by equating strain energy to the kinetic energy of the system. Recalling kinetic energy is equal to $\frac{1}{2}mv^2$ and $v = I/m$, rearranging we get $I^2/2Me$ where I = impulse and Me is the effective mass. The energy balance is solved for I which is the asymptote. Along the impulse asymptote, deflection of the component will not increase even if the pressure is infinitely high. For a constant impulse, as the pressure increases, the load duration must decrease. Thus for an infinitely high pressure the load duration approaches zero.

It now becomes obvious that the relative importance of pressure and impulse is dependent on the characteristics of the component beginning analyzed. Structural parameters including section thickness, span, support conditions and mass are all important to blast resistance. A P-I diagram for an reinforced masonry wall is shown in Figure 5. B1-B4 represent damage levels defined in various guidance documents published by the US Department of Defense. Level B1 is minor or superficial damage while damage level B4 is failure.

We can now examine the problem of relying strictly on peak pressure only as a measure of response. Consider a blast load with a peak pressure of 0.7 psi with an impulse of 20 psi-ms which has a linear equivalent load duration of 57 ms (Figure 6). This is the blast load produced by a 2,200 lb charge at 1300 ft. This peak pressure level is just above the

pressure asymptote for level B2 but the impulse is below the B2 curve because it is the dynamic region of the curve. If we keep the impulse constant and look at other load cases, we can significantly increase the pressure but the response is still at the B2 level. For a peak pressure of 5 psi and impulse still at 20 psi-ms, the response is still at B2 although the load duration is now significantly reduced to about 8 ms to maintain the impulse. This load is approximately that produced by a 25 lbs. charge at 70 ft. A peak pressure of 10 psi with impulse of 20 psi-ms is also B2 response and now the load duration is 4 ms. The response stays the same in these cases, even though the pressure is changing significantly because system response is in the impulsive realm and the peak pressure has little effect. The component is responding to the total load rather than the peak pressure.

Reinforced Masonry Wall

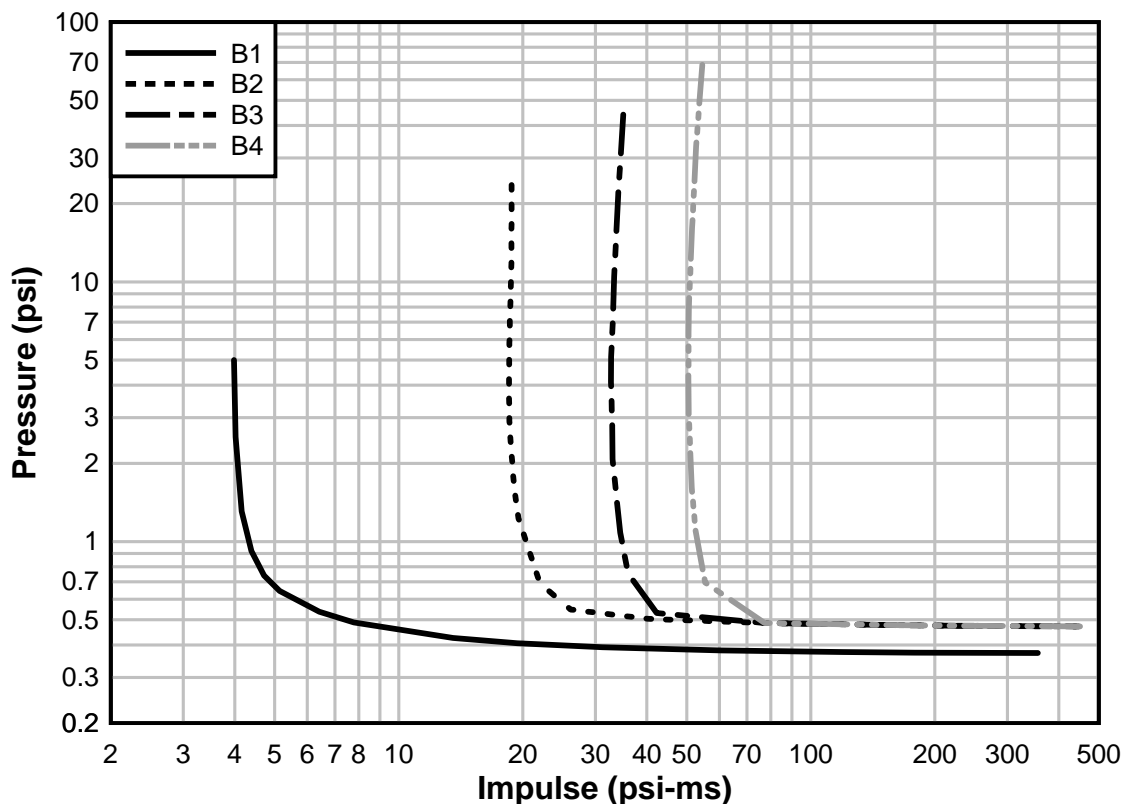


Figure 5 Pressure-Impulse Diagram for Reinforced Masonry

Reinforced Masonry Walls

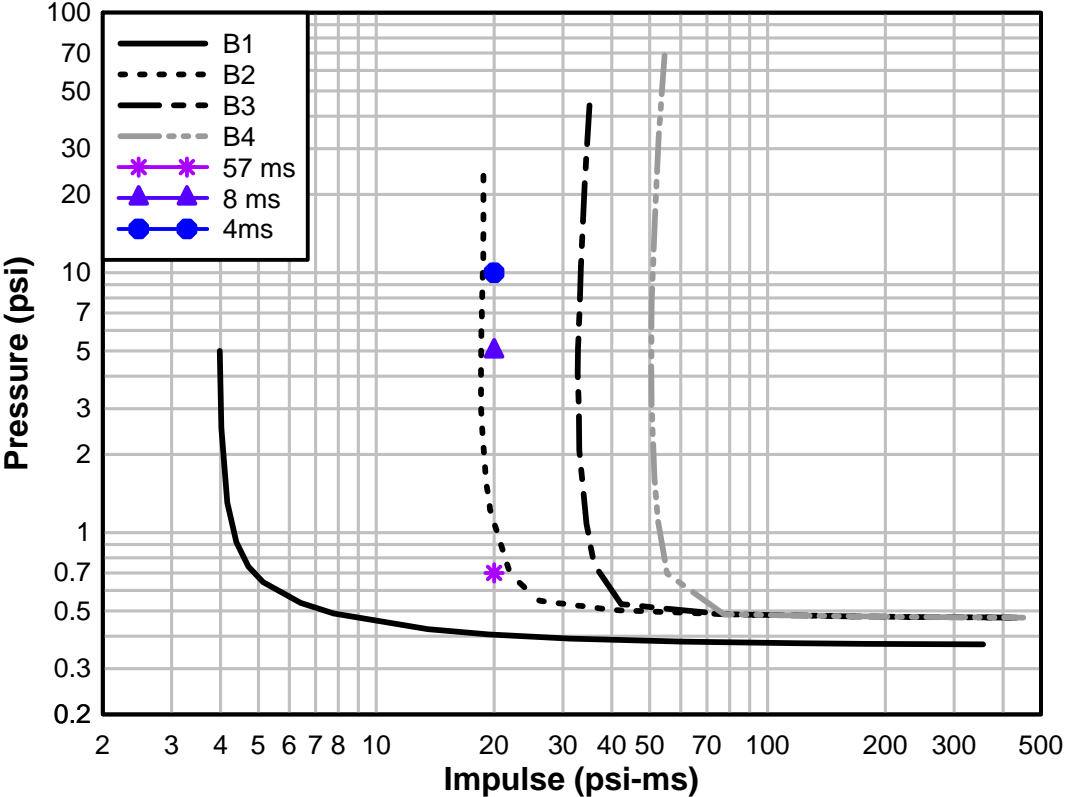


Figure 6 Masonry Wall P-I Diagram With Load Points

We can gain further insight into the sensitivity of the response by manipulating the P-I diagram to create a pressure –duration (P-Td) diagram. In this case a linear pressure time history is used in which $I = P * T_d/2$. For the reinforced masonry wall, the P-Td diagram is shown in Figure 7. Looking at the B2 response curve, we see that for load durations greater than 100 ms, the wall is very sensitive to the peak pressure. In fact the response changes rapidly from B2 to B4 (failure) for very small changes in pressure for blast load durations exceeding 200 ms. For shorter duration loads, the response stays constant even for increasing pressures and these are now lines of constant impulse.

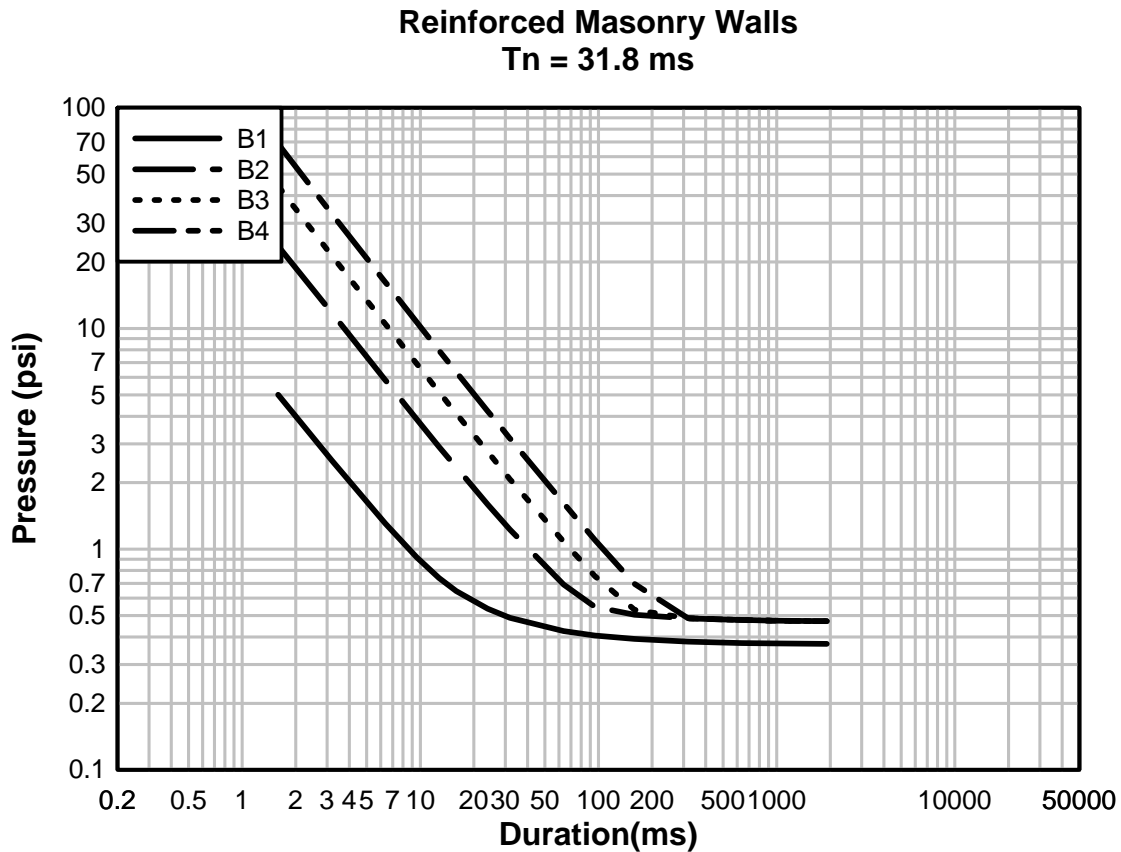


Figure 7 Pressure vs. Duration Diagram

If we modify the P-Td curve by dividing the time points by the natural period of the reinforced masonry wall, we get curves for pressure vs. the T_d/T_n ratio as shown in Figure 8. From this diagram, we can see that for a T_d/T_n ratio of 5, the component is pressure sensitive for a B2 level of response. At T_d/T_n greater than 10, the component is pressure sensitive for all response levels. For T_d/T_n values less than 1, the response is dependent on impulse. A general rule of thumb is $T_d/T_n < 0.3 = \text{impulse sensitive}$ and $T_d/T_n > 3 = \text{pressure sensitive}$ ¹.

Reinforced Masonry Walls $T_n = 31.8 \text{ ms}$

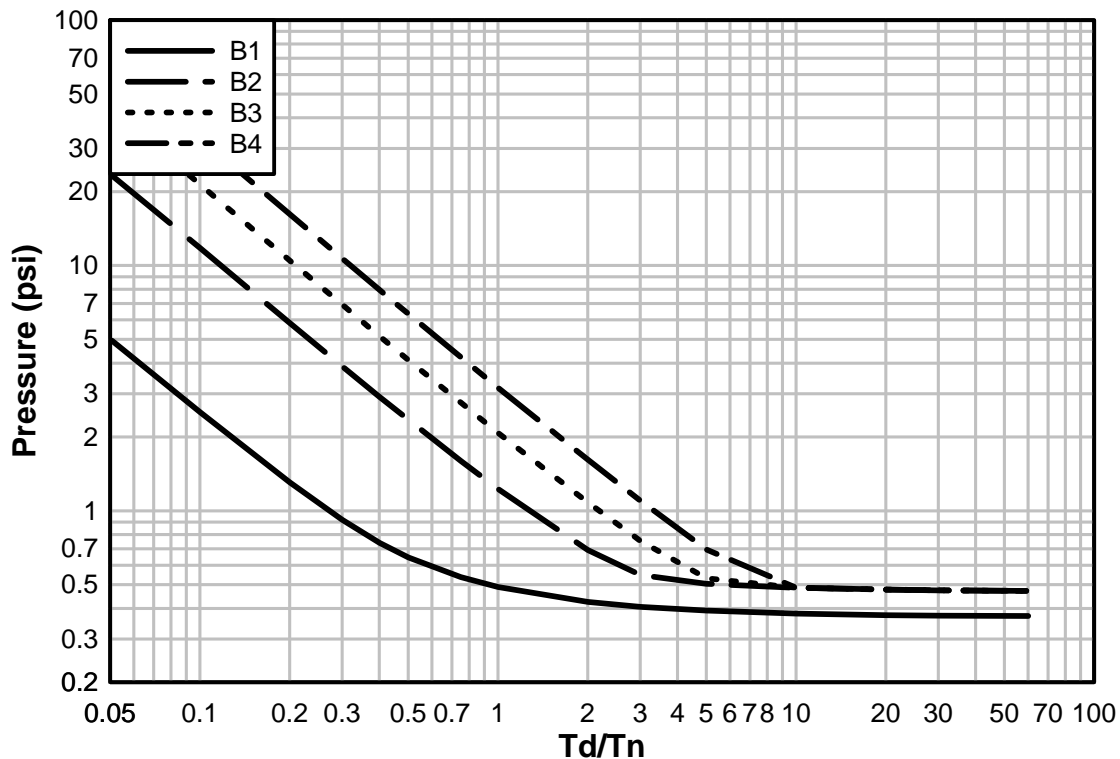


Figure 8 Pressure vs. Duration Ratio

This examination of impulse provides guidance on ways to influence the response through structural retrofit of components. Since the natural period is a function of stiffness and mass, it is often possible to add mass to change the period and make it more impulse sensitive. Additional mass also decreases the demand on the component due to the inertial resistance of the mass.

Damage Tables

Relationships between damage level and peak overpressure have been produced in years past and found their way into a number of guidance documents. Table 1 and Table 2 shows perhaps the most common version of these damage level vs. overpressure relationships. The data is taken from API² but the original data is from Glasstone³ and is based on nuclear weapons test research. Because this testing produced very long duration loads, this data is appropriate for the component response in the pressure sensitive regime. It is not appropriate for short duration loads. Unfortunately, tables of impulse capacity are not available and the analyst must perform dynamic analysis to determine response.

Table 1 Overpressure Effects on Buildings

Building Type	Building Description	Damage Level	Side-on Overpressure to Cause This Damage Level (psi)
B1	Wood frame trailer or shack	Roof and walls collapse	1.0
		Complete collapse	2.0
		Total destruction	5.0
B2	Metal frame/metal clad	Panel failure	1.5
		Walls destroyed	2.5
		Total destruction	5.0
B3	Unreinforced masonry, load bearing	Partial wall collapse	1.0
		Wall collapse	1.25
		Partial roof collapse	
		Complete collapse	1.5
		Total destruction	3.0
B4	Steel/concrete frame with masonry infill	Walls blow in	1.5
		Roof collapse	2.0
		Frame collapse	2.5
		Total destruction	5.0
B5	Reinforced concrete/masonry	Significant wall and roof deflection	4.0
		Major damage and collapse	6.0
		Total destruction	12.0

Table 2 Overpressure Effects on Various Building Components²

Building Component	Reflected Overpressure (psi)	Component Response
Glass	0.2	Breaking
Glass	0.5-1.0	Shattering with body penetrating velocities
Wooden Frame	1.0-2.0	Structural Failure and potential collapse
Steel Cladding	1.0-2.0	Internal damage to walls, ceilings, and furnishings
Concrete-asbestos cladding	1.0-2.0	Shattering
Brick cladding	2.0-3.0	Blown-in
Unreinforced Masonry	1.0-3.0	Wall collapse, possible shattering

It is useful to look at impulse asymptotes for these components since many situations involving explosives result in short duration loads and thus impulse sensitive configurations. Impulse asymptotes for some of the components and response levels in Table 1 are provided in Table 3. There is plenty of uncertainty in this table because the components are not well defined. Component span, cross section, support fixity and mass are not known. The values shown provide some indication capacity but should not be used to make decisions on component response. This caveat also holds true for the pressure levels in the table because the same unknown factors affect response in the pressure sensitive regime.

Table 3 Impulse Effects on Building Components

Building Type	Building Description	Damage Level	Side-on Overpressure to Cause This Damage Level (psi)	Side-On Impulse (psi-ms)
B1	Wood frame trailer or shack	Roof and walls collapse	1.0	30-40
		Complete collapse	2.0	40
		Total destruction	5.0	
B2	Metal frame/metal clad	Panel failure	1.5	30
		Walls destroyed	2.5	100
		Total destruction	5.0	
B3	Unreinforced masonry, load bearing	Partial wall collapse	1.0	25
		Wall collapse Partial roof collapse	1.25	30-40
		Complete collapse	1.5	
		Total destruction	3.0	
B4	Steel/concrete frame with masonry infill	Walls blow in	1.5	50
		Roof collapse	2.0	250
		Frame collapse	2.5	300-500
		Total destruction	5.0	
B5	Reinforced concrete/masonry	Significant wall and roof deflection	4.0	150-200
		Major damage and collapse	6.0	200
		Total destruction	12.0	

Debris

Impulse, rather than pressure is the dominant parameter when evaluating debris hazards. Once a component breaks apart, the initial velocity (V) is a function of the applied impulse (I): $V = I/M$ where M is the effective mass. Peak pressure would not give an indication of the debris hazard for most situations of interest.

Conclusion

Blast impulse is an important driver of response for both structural and non-structural components. In many situations, response is primarily due to impulse rather than peak pressure. Unfortunately, because pressure is more intuitive than impulse to most people, blast capacity is often described in terms of peak pressure. Those interested in assessing blast damage would be well served to analyze response to impulse and develop a “feel” for the impulse capacity of components. This approach will provide improved guidance for rapid assessment of structures and retrofit design.

References

1. L. Louca, J. Friis, S.J. Carney, “CTR 106 Response to Explosions” Health and Safety Executive, November 2001
2. API, “Management of Hazards Associated with Location of Process Plant Buildings”, API Recommended Practice 752, American Petroleum Institute, 1995.
3. S. Glasstone and P. J. Dolan (eds.), **THE EFFECTS OF NUCLEAR WEAPONS**, US DoD/DOE, Washington, D.C., 3rd ed., 1977.

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Explosives Safety Seminar**

The Case for Impulse

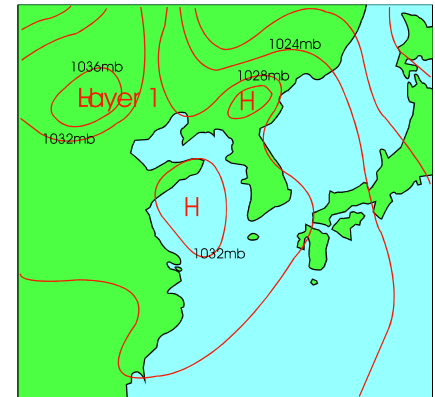
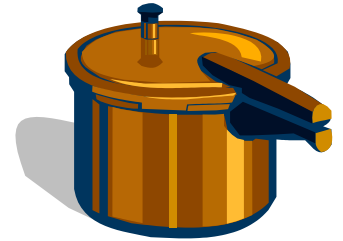
**Presented by:
Darrell D. Barker, P.E.**

Presentation Outline

- Focus on Pressure
- Impulse and Duration– the other factors
- Response – pressure vs. impulse
- Damage tables
- Debris
- Conclusions

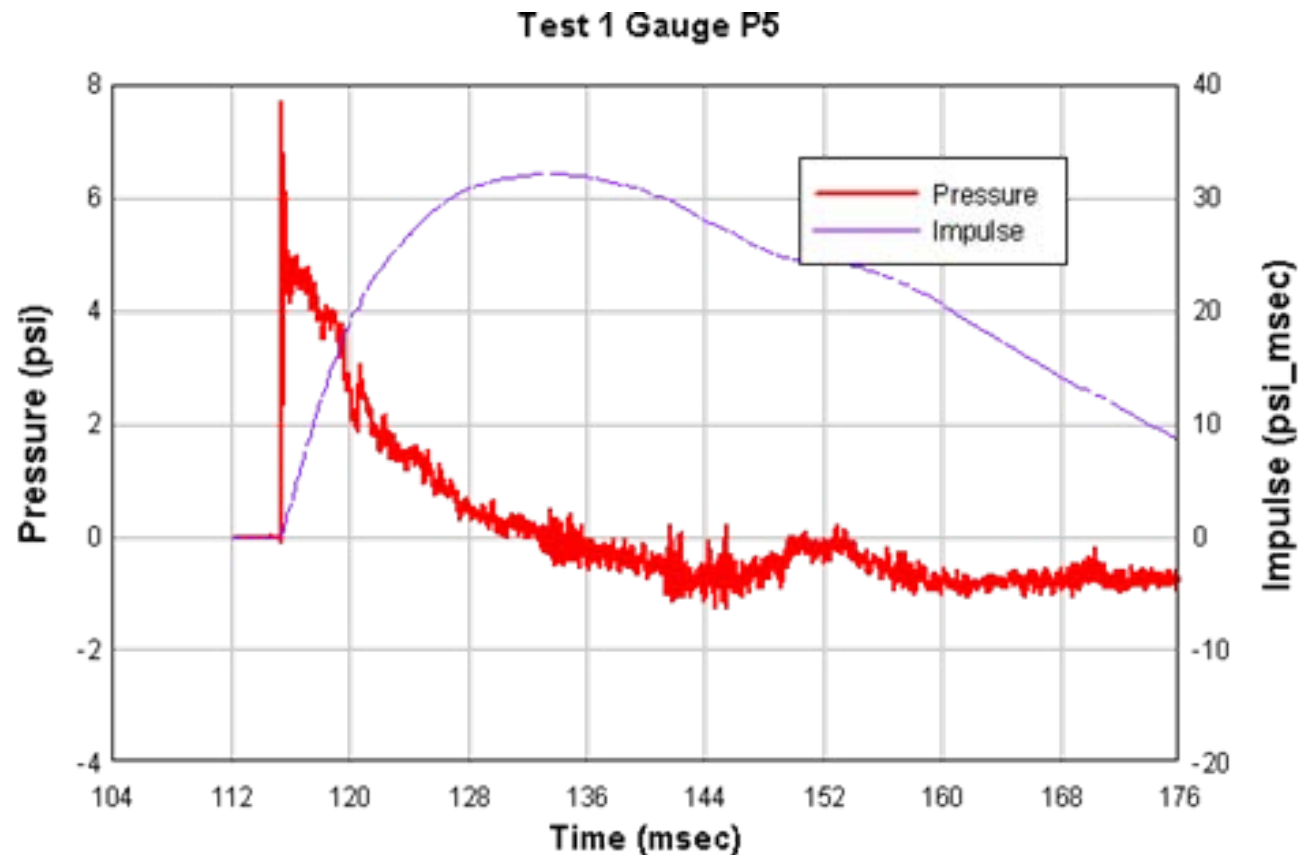
The Focus on Pressure

- Damage to buildings and components often described in terms of applied overpressure
- Pressure is:
 - intuitive
 - one-dimensional
 - easy to relate to common physical phenomena

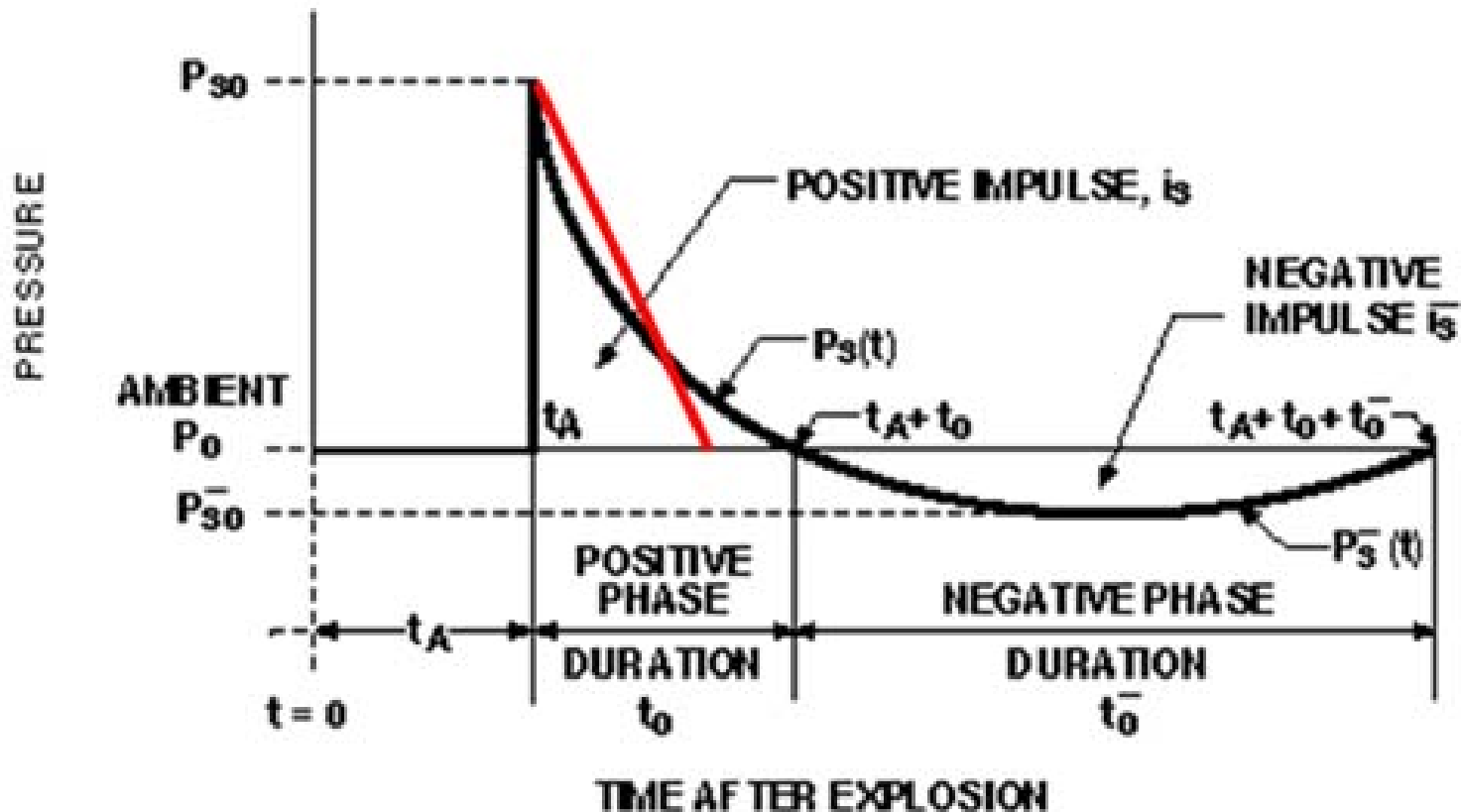


Impulse and Duration – The Other Factors

- Peak pressure is one component
- Impulse is total applied load

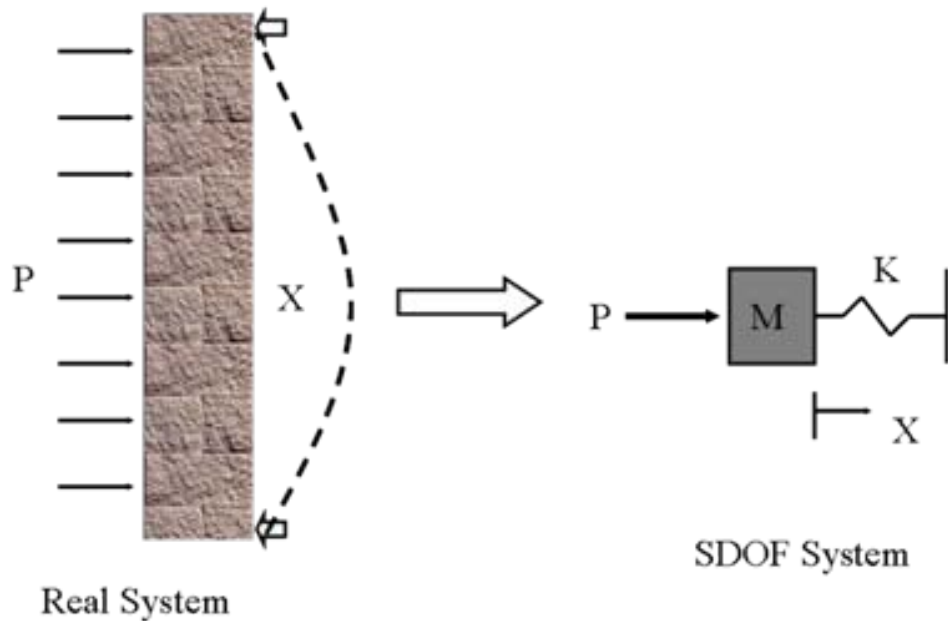


Impulse and Duration – The Other Factors



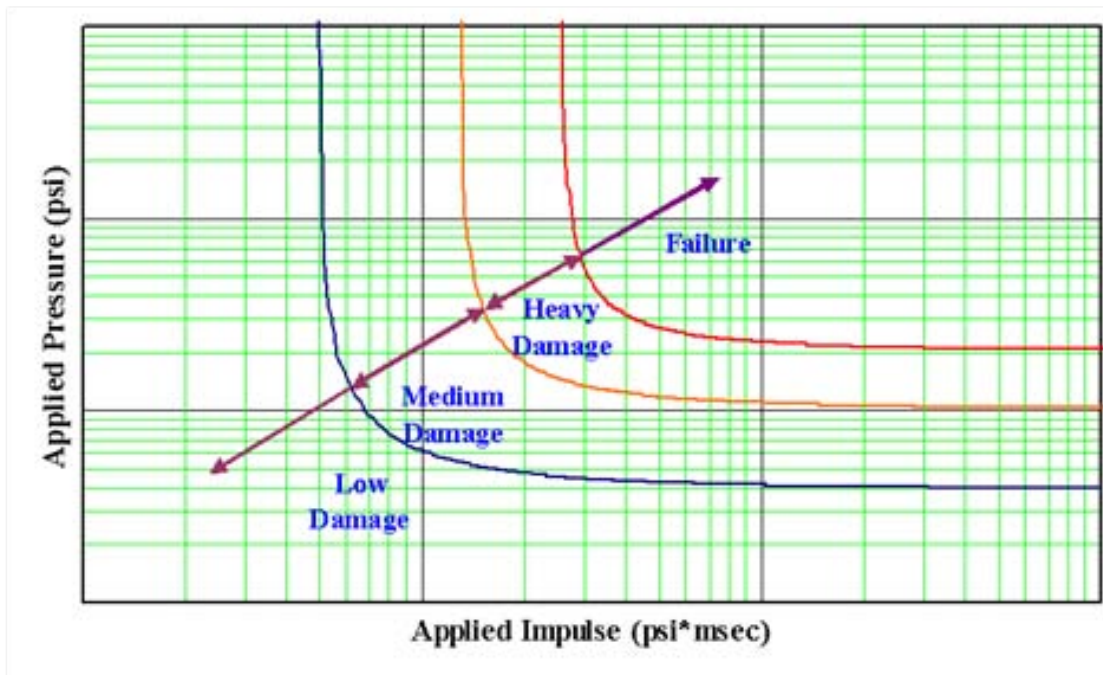
Response – Pressure vs. Impulse

- Dynamic response
- SDOF analysis



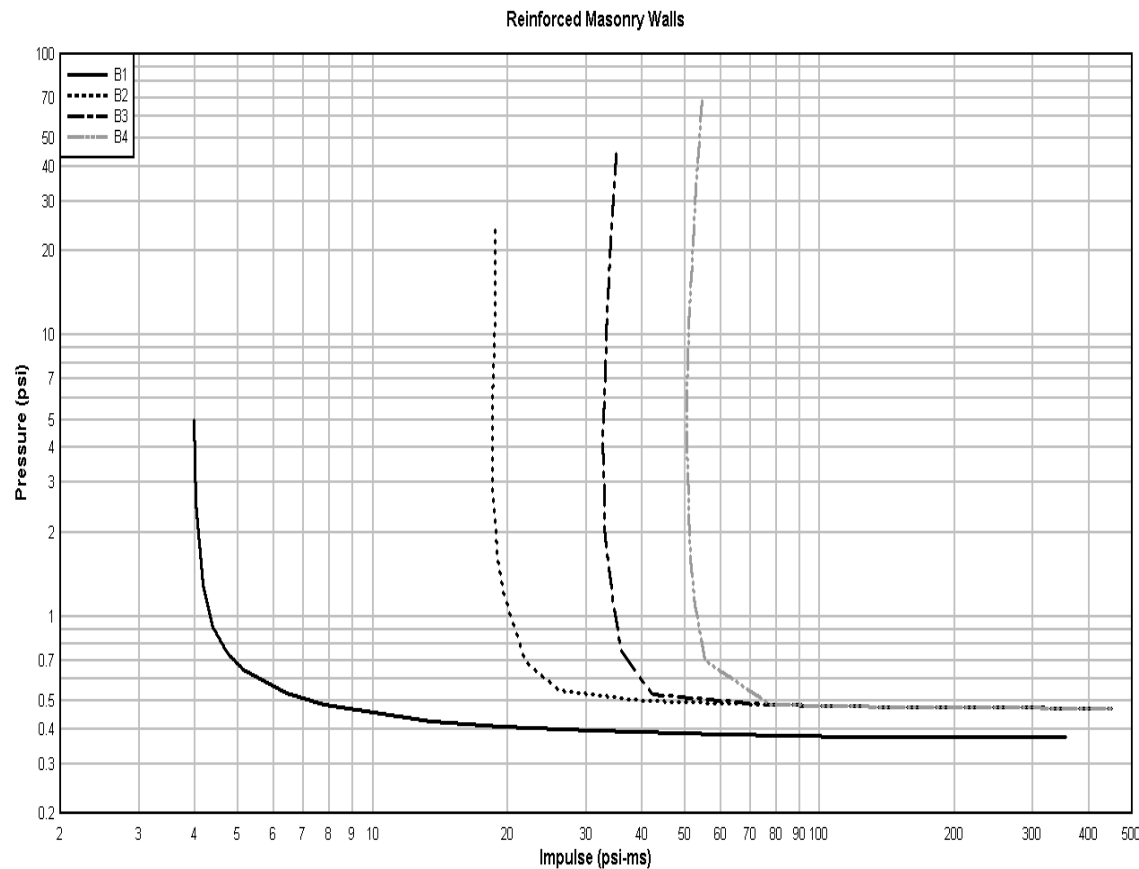
Response – Pressure vs. Impulse

- P-I diagram constructed from SDOF properties and energy balance
 - Pressure – work done vs. strain energy
 - Impulse – kinetic energy vs. strain energy



Response – Pressure vs. Impulse

- Reinforced Masonry P-I
- 12', 8" block



Response – Pressure vs. Impulse

- Response Levels

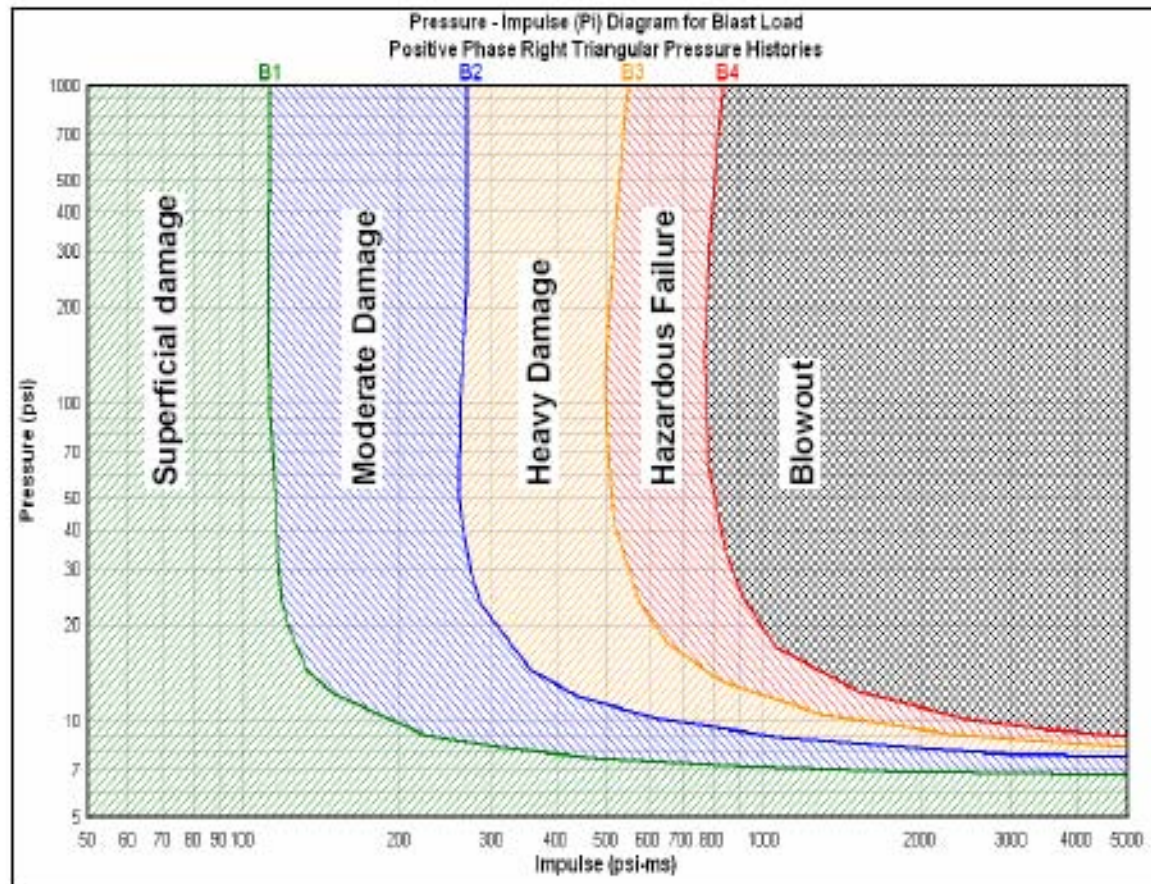
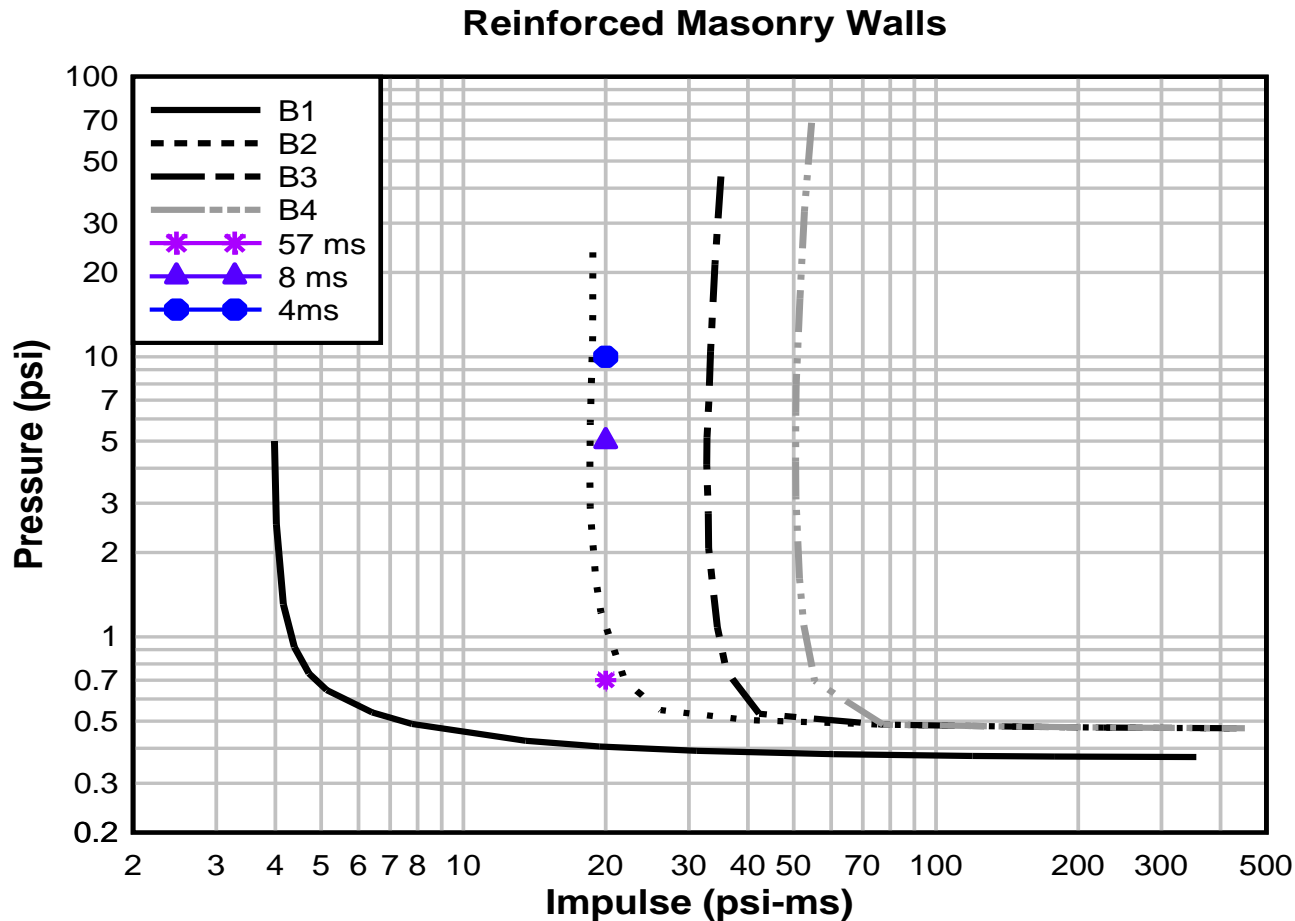


Figure 3-4 Pressure Impulse Diagram Showing Component Damage Levels

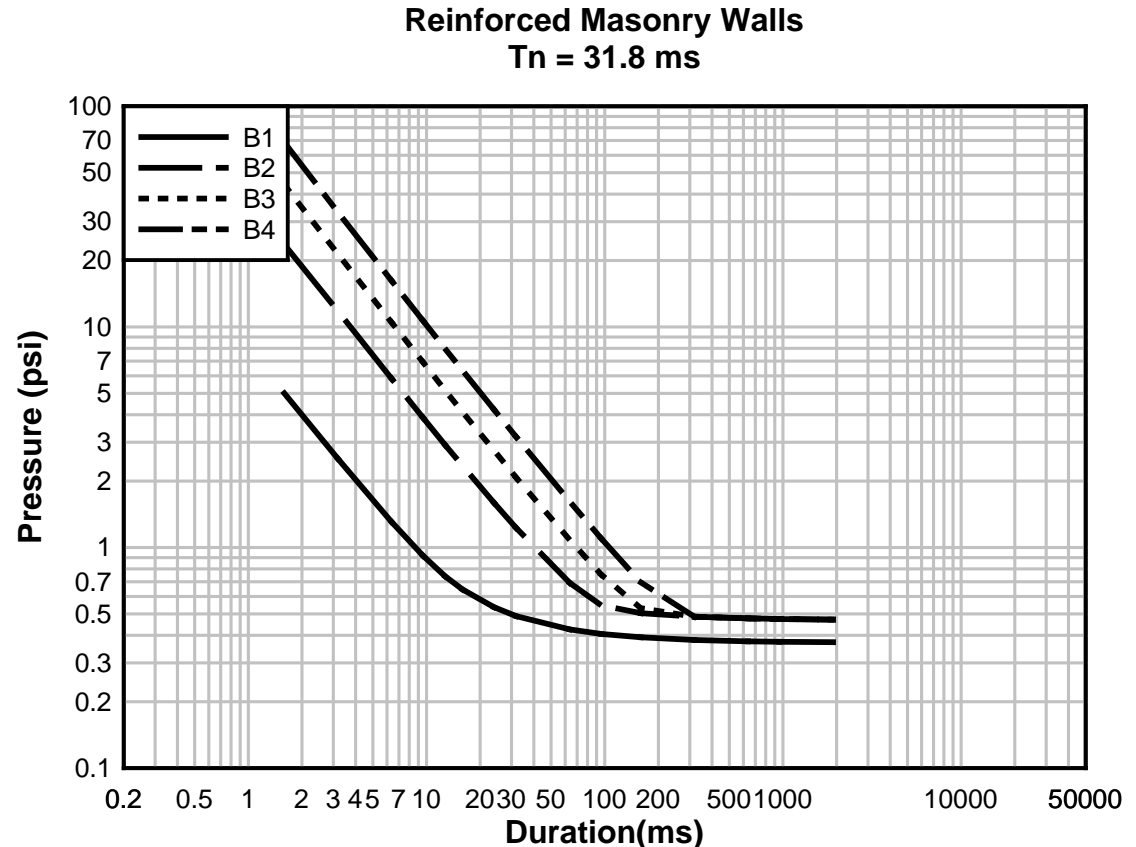
Response – Pressure vs. Impulse

- Constant impulse = constant response



Response – Pressure vs. Duration

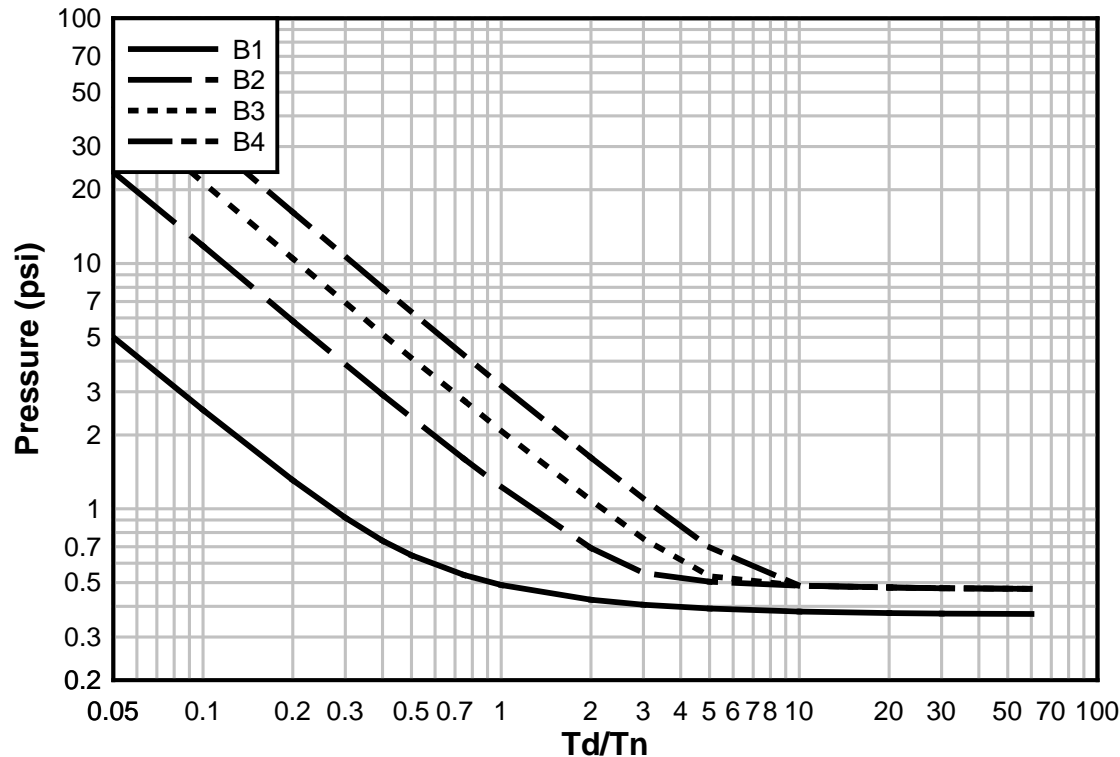
- Convert impulse to equivalent duration
- Shows duration at which response becomes impulse sensitive



Response – Pressure vs. Duration Ratio

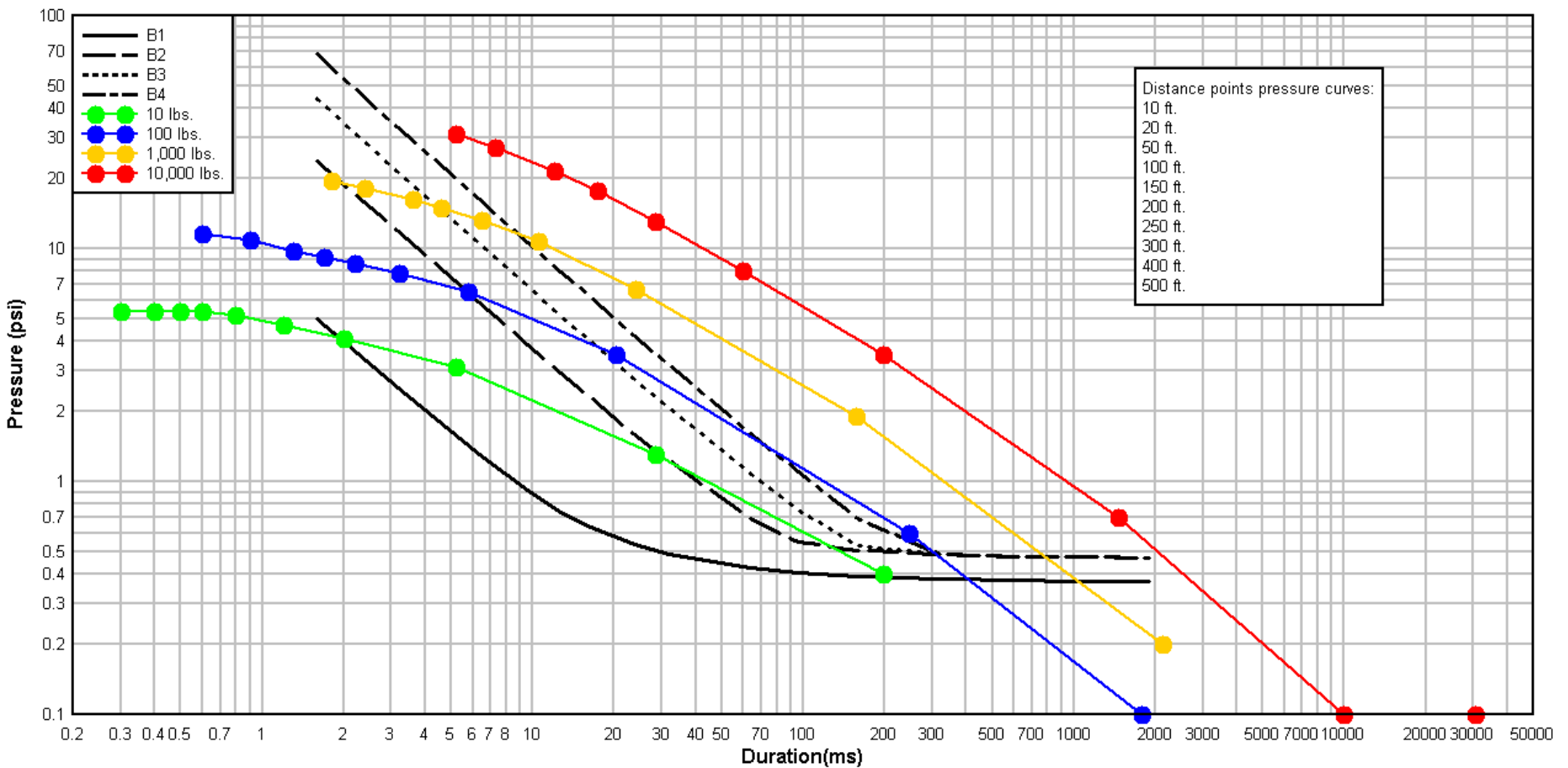
- Impulse control $T_d/T_n < 1$
- Pressure control $T_d/T_n > 10$

Reinforced Masonry Walls
 $T_n = 31.8 \text{ ms}$



Charge vs. Standoff

Reinforced Masonry Walls
 $T_n = 31.8 \text{ ms}$



Damage Tables

- Vague damage description
- Structural properties unknown

Building Type	Building Description	Damage Level	Side-on Overpressure to Cause This Damage Level (psi)
B1	Wood frame trailer or shack	Roof and walls collapse	1.0
		Complete collapse	2.0
		Total destruction	5.0
B2	Metal frame/metal clad	Panel failure	1.5
		Walls destroyed	2.5
		Total destruction	5.0
B3	Unreinforced masonry, load bearing	Partial wall collapse	1.0
		Wall collapse Partial roof collapse	1.25
		Complete collapse	1.5
		Total destruction	3.0
B4	Steel/concrete frame with masonry infill	Walls blow in	1.5
		Roof collapse	2.0
		Frame collapse	2.5
		Total destruction	5.0
B5	Reinforced concrete/masonry	Significant wall and roof deflection	4.0
		Major damage and collapse	6.0
		Total destruction	12.0

Damage Tables

- With impulse control values

Building Type	Building Description	Damage Level	Side-on Overpressure to Cause This Damage Level (psi)	Side-On Impulse (psi-ms)
B1	Wood frame trailer or shack	Roof and walls collapse	1.0	30-40
		Complete collapse	2.0	40
		Total destruction	5.0	
B2	Metal frame/metal clad	Panel failure	1.5	30
		Walls destroyed	2.5	100
		Total destruction	5.0	
B3	Unreinforced masonry, load bearing	Partial wall collapse	1.0	25
		Wall collapse	1.25	30-40
		Partial roof collapse	1.5	
		Complete collapse	3.0	
B4	Steel/concrete frame with masonry infill	Total destruction	5.0	
		Walls blow in	1.5	50
		Roof collapse	2.0	250
		Frame collapse	2.5	300-500
B5	Reinforced concrete/masonry	Total destruction	5.0	
		Significant wall and roof deflection	4.0	150-200
		Major damage and collapse	6.0	200
		Total destruction	12.0	

Debris

- Debris range dependent on initial velocity
- Initial velocity a function of net applied impulse and mass
- $V = I_a / M_e$
- $I_a = \text{gross impulse} - \text{failure impulse}$

Conclusions

- Structural damage due to blast loads most often related to pressures but only half the story
- Understanding the interrelationship between strength, mass and load duration is critical to damage prediction and blast mitigation
- Impulse is much less intuitive but often much more important to response than pressure